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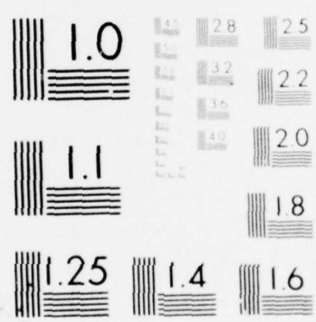

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ION BEAM SUPERPOLISHING OF METAL MIRRORS FOR HIGH ENERGY LASERS

December 1975

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A new process has been developed which employs a low energy ion beam to superpolish metal surfaces. The process is applicable in principle to all metals. This technique overcomes the tendency of metal surfaces to develop etch patterns and other surface irregularities during ion beam bombardment. The process produces superpolished optical surfaces significantly superior to those formed by conventional optical polishing or metallurgical techniques. Because ions of inert gases are employed (Cont)

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20. ABSTRACT (Cont)

for the superpolishing process the resultant surface is uncontaminated in contrast to conventional optical, chemical or metallurgical methods which result in diffusion of abrasion contamination or "bronzed" surfaces. In addition, this process may be employed for final figuring of optical surfaces.

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INTRODUCTION

High Energy Lasers place severe demands on optical elements which intercept the laser beam or form the laser cavity. Because very high power densities must be handled by large aperture optics the energy absorbed by the optical element must be minimized. Two different techniques are used to dissipate the thermal heat load on the mirrors: heat transfer using a continuous flow of cooling fluid or alternatively using a massive mirror in order to create a heat sink. Figure 1 is a photomicrograph of the surface of a copper mirror which was used to form the cavity of a High Energy Laser. The surface of this mirror is characterized by damage sites such as the one shown.

It is generally accepted that surface preparation strongly influences laser induced surface damage[1]. Bennett et al[2,3] showed that the absorption of light increases with increasing roughness of metal surfaces. Several theories[4,5,6] have been advanced to explain the microscopic mechanism of laser induced damage which is variously attributed to different causes. Experimental studies of laser induced surface damage both to metals and to dielectrics indicates a very strong correlation of surface damage threshold levels to microscopic cracks, scratches, inclusions, pores and localized inhomogeneities at or near the surface[7,8,9].

CLASSICAL METHODS

The standard methods of forming optical elements are ancient, the origins of these methods predating the optical industry[10]. Essentially, the process shapes and polishes optical surfaces by mechanical abrasion of an oversize workpiece, removing material from the source by erosion. As the desired surface contour is approached course grinding tools are replaced by fine grain polishing substances, such as pitch laps, barnsite, or rouge. These methods are capable of producing very smooth surfaces (approximately 1 nanometer RMS roughness) on glass. The methods used by metallurgists are similar if large area smooth surfaces of precise contour are desired.

Power densities of as much as $10^4 w/cm^2$ are encountered by High Energy Laser cavity mirrors. Metal mirrors are required to dissipate the thermal load imposed because the best practically obtainable absorptivity will be of the order of 0.001.

Figure 1. OHFC Copper Mirror Surface Damaged By High Energy Laser
(Magnification 100 Diameters)

Classical optical fabrication techniques have been applied to form metal mirrors for High Energy Laser systems with only marginal success. Figure 2 is an optical photomicrograph of a copper mirror fabricated at Frankford Arsenal for a High Energy Laser using classical optical techniques. The surface is characterized by surface scratches of the order of 0.1 to 10 micrometers width which are formed by the polishing substance. Figure 3 is a photograph of the same copper surface showing the surface scatter effects caused by the scratches. In addition to the problem of microscopic surface defects, the process of abrasing the surface with the polishing material has been shown to cause diffusion of the polishing substance into the mirror near-surface layer. The resultant dispursed inhomogeneities cause the finished mirror to be very vulnerable to irreversible thermal damage. It should be noted that copper mirrors such as shown in Figures 2 and 3 represent the state of the art in conventional metal polishing and have been favorably compared with the best available from private industry. Frankford Arsenal's Optical Shop has supplied the Army TSL with many mirrors of various materials including molybdenum, OFHC copper, aluminum and stainless steel.

POINT CONTACT POLISHING

Much work has been done recently using diamond tools to superpolish metal surfaces. Most of the work in this area has been sponsored by the Atomic Energy Commission. Point contact polishing - also called micromachining - has been successfully applied to the fabrication of metal flats and spheres. Figure 3 is a photomicrograph of the surface of a micromachined copper mirror.

Table 1 lists some properties of polished surfaces measured at 632.8 nanometers.

Table 1. Polished Surfaces Measured at 632.8 Nanometers (Ref. 11)

SAMPLE	TOTAL INTEGRATED SCATTER (%)
Point Contact Polished Aluminum	0.35
Point Contact Polished Copper	0.2
Super Polished Copper	0.015
Nickel	0.01
Beryllium Sputtered on Polished Beryllium	0.005
Super Polished Fused Silica	0.002

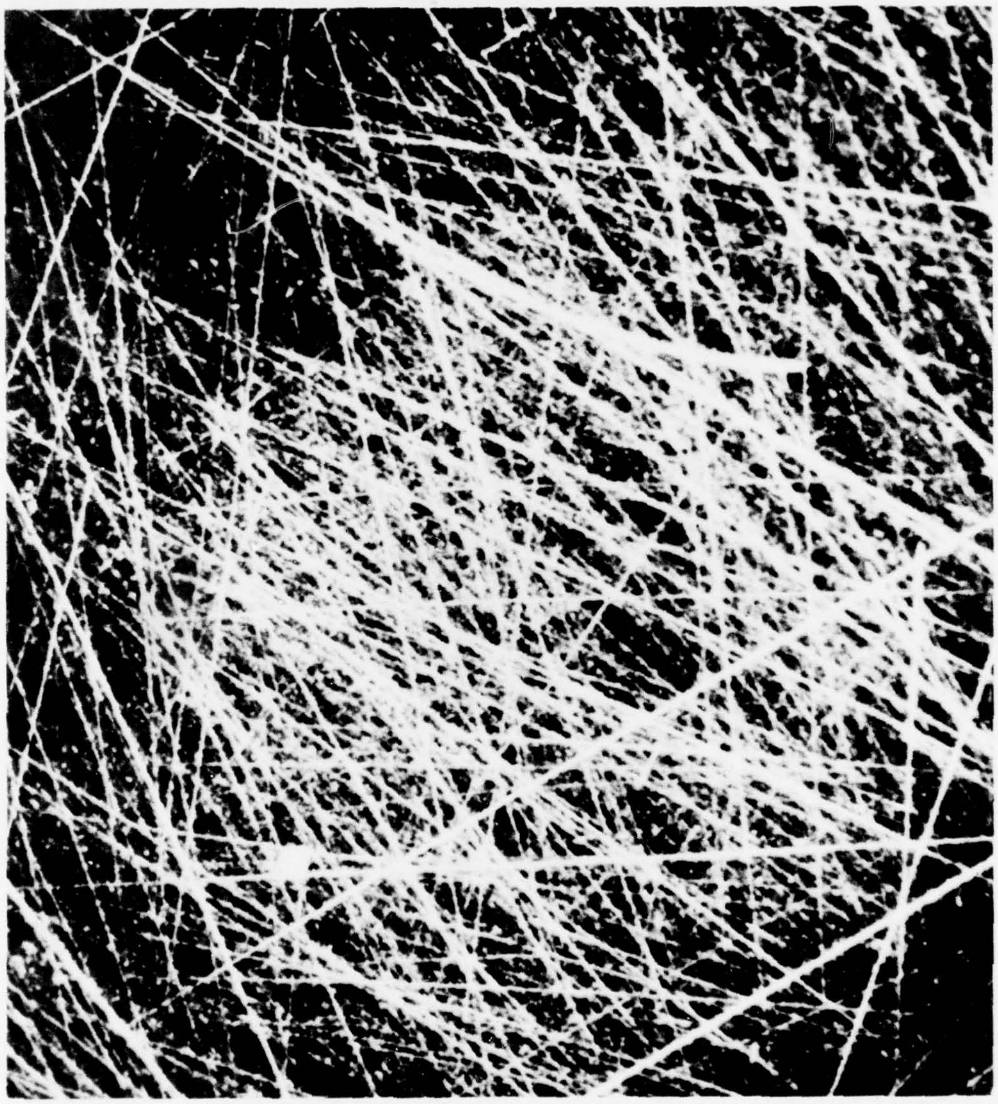

Figure 2. OFHC Copper Mirror Surface Conventional Polish (Magnification 200 Diameters)

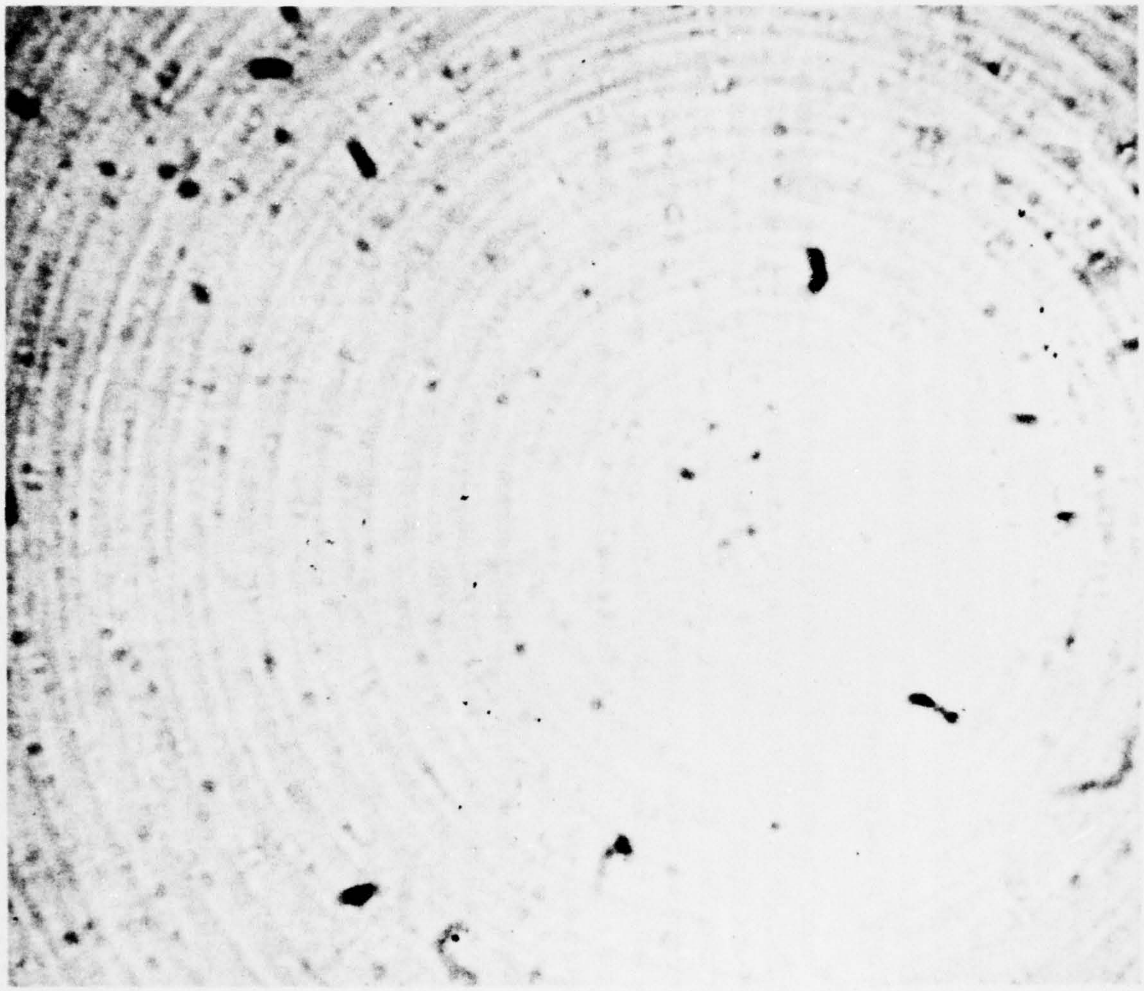

Figure 3. Point Contact Polished OFHC Copper Mirror
(Magnification 200 Diameters)

ION BEAM SPUTTERING

A new method of figuring and polishing glass surfaces has been developed at Frankford Arsenal[12]. This system utilizes a focused beam of heavy ions to shape and polish optical surfaces by means of controlled sputtering. At the relatively low ion energies (<60 KeV) employed in the figuring and polishing process, the ion-surface atom interactions are characterized by elastic nuclear collisions. Atoms are removed from the solid as a result of a momentum transfer from the incident ion to the atoms of the target solid. This process is called sputtering. A short summary of the microscopic details of the sputtering process may be found in reference 12.

In general, the surface of a material bombarded by an ion beam undergoes marked changes in both macro and micro structure. After ion beam sputtering, the resultant surface morphology is, in general, a function of the structure of the bulk material. If the material is amorphous as simulated by Figure 4, the ion beam eroded surface will generally be smoother (on a microscopic scale) than the initial surface. This is due to the preferential sputtering of local micro high peaks at a faster rate than the rest of the surface and the decrease in yield from micro depressions.

The cause of this fortunate polishing mechanism may be simply explained by geometric considerations. In brief, atoms comprising micro 'hills' or 'high peaks' are surrounded by free space in a solid angle greater than 2π steradians; atoms comprising the surface or near surface of the average surface level are surrounded by approximately 2π steradians of free space; and stoms lying within a local depression are surrounded by less than 2π steradians of free space. Since the escape probability of an atom from the target after a momemtum transfer interaction with an energetic particle is proportional to the range of the atom and the surface area within this range, local high peaks will be preferentially sputtered and local 'pits' will suffer a relative decrease in sputter yield; thus continued sputtering tends to smooth amorphous surfaces on a microscopic basis.

Surfaces of crystalline materials (such as metals) react quite differently to ion beam erosion. Whereas amorphous materials exhibit no long range ordering of atomic position and can be treated as if the atomic positioning were completely random, crystalline or polycrystalline materials have long range ordering of atoms. This ordering, in general affects the resultant ion beam sputtered surface microstructure very strongly and, in many cases, causes the final surface to be decorated in a deep and undesired pattern. Figure 5 simulates a polycrystalline surface undergoing ion beam sputtering. The ordering of the atoms in the crystal results in an efficient transfer of momentum resulting in a high probability of preferential sputtering of atoms at defect sites. The inter-

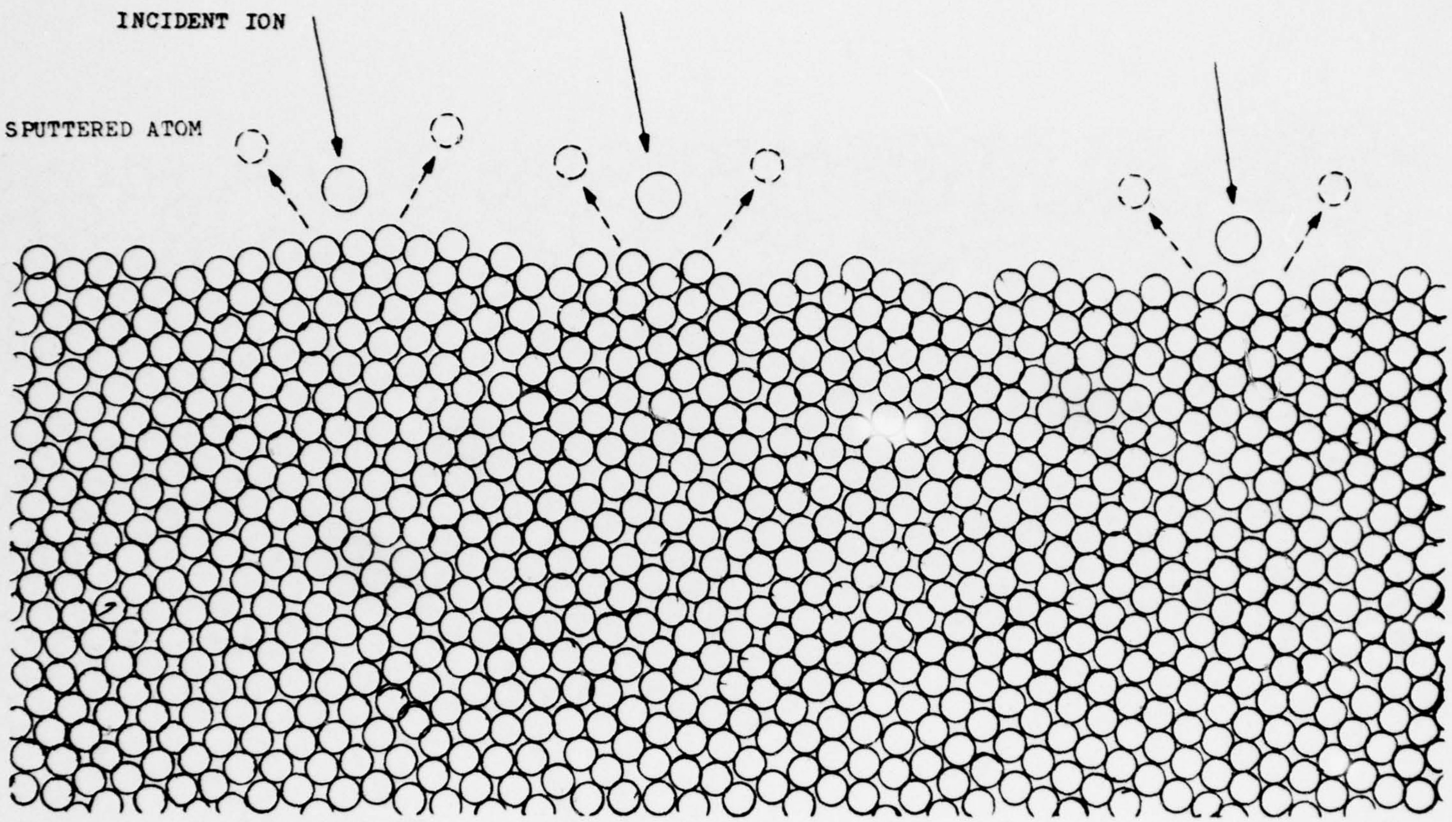

Figure 4. Ion Beam Sputtering of Amorphous Material

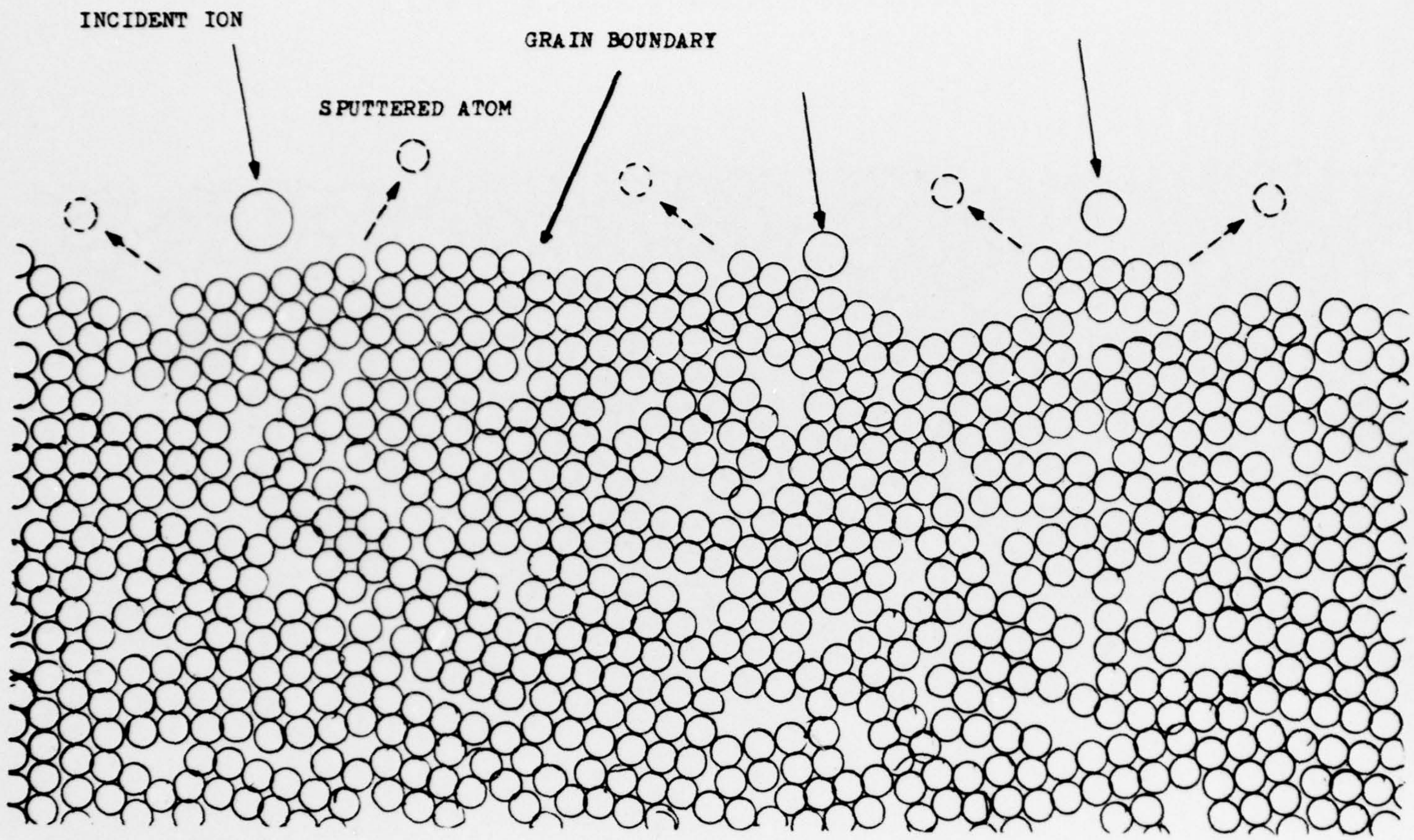

Figure 5. Ion Beam Sputtering of Polycrystalline Material

actions which are involved are very complicated and long ranged; and are strongly dependent on the lattice structure, lattic defects (both point and line), lattice orientation with respect to the crystal surface and with respect to the angle of incidence of the ion beam and the energy of the ion beam the interactions which have strong effects on surface quality are channelling, Cronodian collisions, and focusing sequences.

Figures 6 and 7 are photomicrographs of a copper surface after ion beam erosion. Note that the surface is extremely rough as a result of preferential sputtering.

ION BEAM SUPERPOLISHING OF METAL MIRRORS

The Frankford Arsenal solution to the surface decoration due to preferential sputtering of crystalline materials is essentially an end run around the problem. If an ion beam will increase the roughness of a crystalline surface, then the solution is to make sure that the metal surface is essentially non-crystalline before superpolishing with the ion beam. If a perfect crystal is defined as being constructed by the infinite regular repetition in space of identical structural units of atoms, then crystallinity is destroyed proportionately as the spatial ordering of the atoms in the material is randomized.

When a polycrystalline surface is subjected to mechanical grinding and polishing the crystallinity of the surface and near-surface is damaged. The resultant microstructure has very fine grain size (very small crystallites) and high defect density. This type of structure represents a fair approximation of an amorphous surface. Figure 8 is a representation of such a surface. The structure of the surface and near-surface is effectively amorphous because of the extremely small grain size and random orientation of the grain. The underlying material is polycrystalline. Ion beam sputtering of the damaged surface layer will proceed in a manner typical of amorphous materials i.e., the surface will become smoother. Figure 9 is a photomicrograph of a OFHC copper mirror surface which has been mechanically polished using a polishing compound containing an $Al_2 0_3$ grit. The surface is covered with scratches with cross-sections of the order of a micrometer. Figures 10 and 11 are photomicrographs of the same surface after approximately one hour erosion with an ion beam. The beam was incident on the surface at near grazing angle. Singly ionized argon ions at 30 KeV potential were used to perform the sputtering.

On each photomicrograph there can be seen small grains with long streamers apparently originating at the grain. This effect is due to a fortunate accident. The grains are pieces of the polishing grit $Al_2 0_2$ imbedded on the surface of the copper. This is a common occurrence due to the relative softness of the

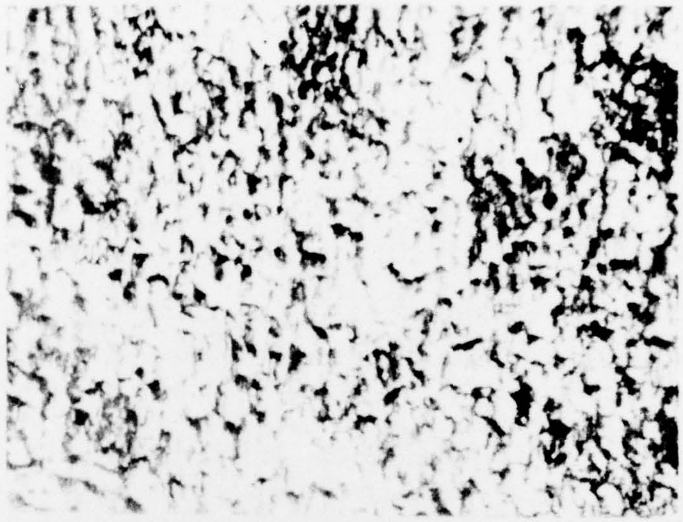

Figure 6. Copper Sample, after 3-Hour Erosion Grazing Incidence

Figure 7. Copper Sample, after 5-Hour Erosion Grazing Incidence

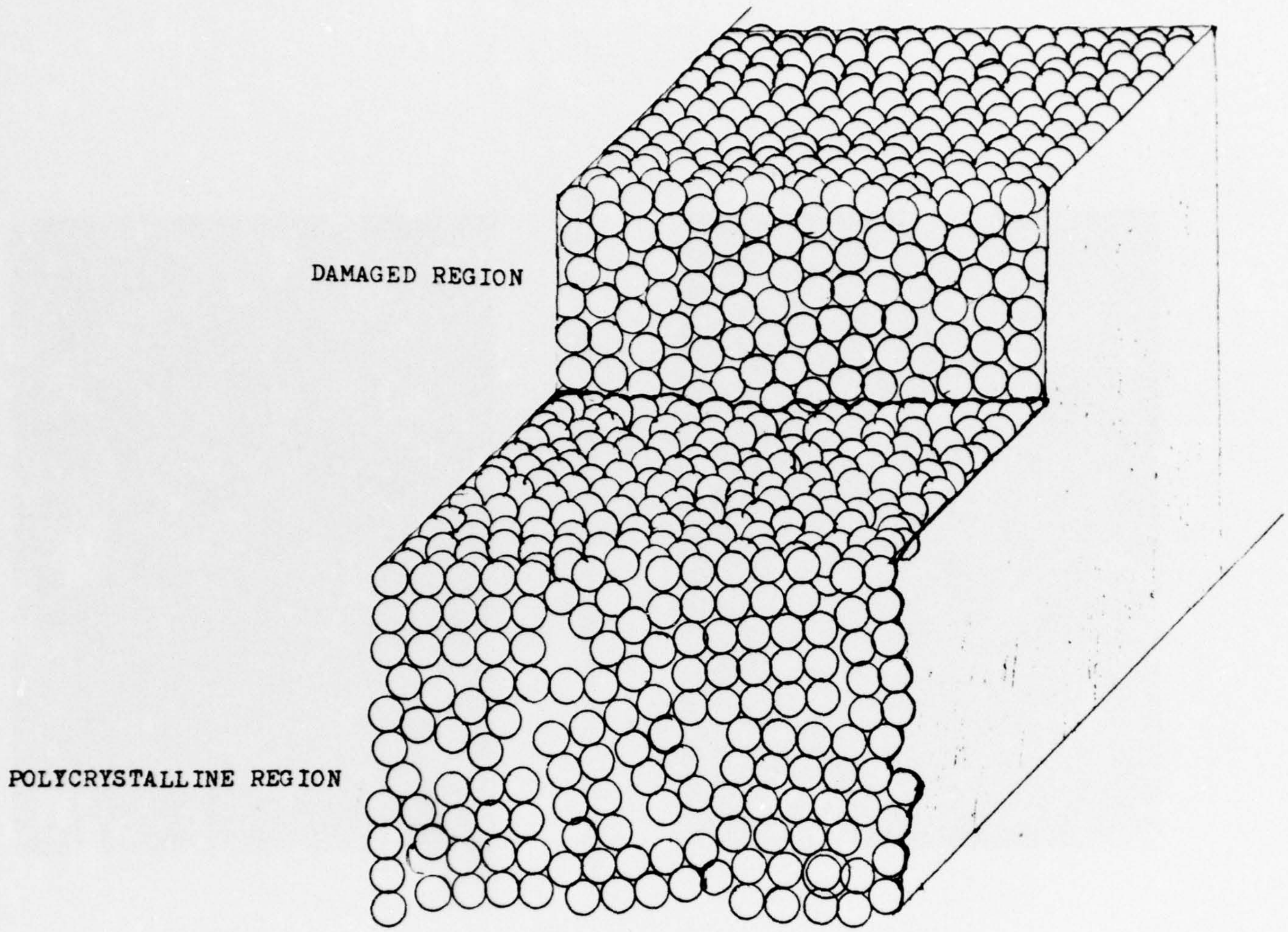

Figure 8. Symbolic Representation of Metal Mirror Surface

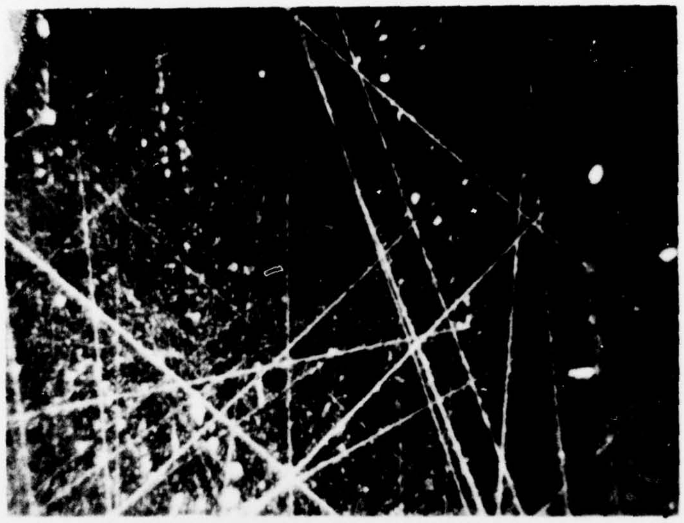

Figure 9. Photomicrograph of Original Copper Surface

Figure 10. Photomicrograph of Copper Surface after Ion Beam Erosion

Figure 11. Ion Beam Superpolished OFHC Copper Surface
(Note Al_2O_3 Particle and "Tail" Discussed in Text)
Magnification 1500 Diameter

copper. These grains were accidently left on the surface of this particular sample and not cleaned off before sputtering. The grains of Al_2O_3 stick up several micrometers from the level of the surface and acted like small umbrellas shielding a small region of the surface from the ion beam which was incident at almost grazing angle. What looks like a tail is the copper surface which was not eroded by the ion beam. This fortunate accident permits the side by side comparison of the original polished surface with the ion beam superpolished surface. Note that many scratches which are visible in the original surface have been completely removed from the superpolished region and the few very deep scratches which have not been removed are distinctly shallower.

An attempt was made to remove all the scratches - including the deepest - from a large (25 cm diameter) OFHC copper mirror. Figure 9 is a dark field photomicrograph of the original surface after optical polishing but before the surface was ion beam superpolished. The surface was then uniformly scanned at the low grazing angle by the ion beam (uniform integrated total incident ions per unit surface area). The process continued for approximately forty hours, however, the mirror was inspected and rotated 90 degrees about the surface normal every four hours. The goal was to achieve a surface on which no defects would be visible under high power phase contrast interference microscopic examination. The polishing process was halted when the surface shown by the photomicrograph in Figure 12 was observed. What had happen was that in the attempt to achieve a zero defect surface, the ion beam had eorded completely and uniformly through the damaged layer of the surface and reached the undamaged polycrystalline region. As the ions struck this region, preferential sputtering caused the severe decoration of the surface and resulted in the rough surface shown.

Mechanical optical polishing alone cannot be used to prepare the surface of a metal mirror for ion beam superpolishing. The scratches shown on the surface of the OFHC copper mirror in Figure 9 extend down to the polycrystalline region shown by Figure 12. This is reasonable since the scratches are due to the mechanical polishing process and the damage likewise due to the mechanical polishing process - indeed the depth of the scratches should logically define the greatest possible depth of the damaged near-surface layer.

This drawback may be overcome by increasing the depth of the damaged region without increasing the depth of the scratches. This is achieved by coating the surface with a amorphous metal layer. The metal layer is deposited at high vacuum ($< 10^{-5}$ torr), and care must be taken to prevent oriented growth. There exist several proven thin film techniques which permit this type of deposit and the process is simplified because the substrate in this is thoroughly damaged

Figure 12. Ion Beam Superpolished OFHC Copper Surface
(Surface Sputtered Down to Polycrystalline Region)
Magnification 200 Diameters

by the optical polishing process. The thin film deposit on the metal surface does not eliminate the scratches or other surface roughness present on the original surface - it simply uniformly coats the surface, preserving essentially the same roughness. The thin film overcoat does, however, increase the depth of the damaged region without increasing the depth of the roughness. This permits the ion beam superpolishing process to smooth the surface without getting down to the polycrystalline region. Thermal evaporation has been successfully used in the laboratory to prepare the surface for an ion beam superpolishing. Both RF sputter and ion plating systems are being assembled for future coatings. The ion plating technique represents the most promising coating method since the thin film layer is formed by relatively high momemtum incident ions of the element which is being coated. Some investigators have reported room temperature recrystallization of deposited thin metal film surfaces which have been formed by RF sputter techniques[13]. Other investigators have developed viable methods to prevent recyrstallization[14]. No adverse effects due to recrystallization has been noted in this laboratory.

FIGURING METAL MIRRORS

The ion beam sputtering process is capable of figuring (shaping the contour) a metal surface as well as superpolishing. In effect, a required optical figure may be formed by varying the number of ions incident on each elemental surface area as a linear function of the amount of material to be removed to achieve the desired contour. This process has been described previously[12]. To date, no attempt has been made to apply this process to metal mirrors, however, the techniques has achieved precise contours in glass.

CONCLUSIONS

A new superpolishing technique has been described which has been successfully applied to OFHC copper mirror surfaces. The process is applicable to all materials. Because inert gas ions are employed for the superpolishing process the resultant surface is uncontaminated - in contrast to surfaces formed by conventional optical or metallurgical methods. In addition the process is capable of shaping optical contours.

ACKNOWLEDGEMENTS

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